TECHNOLOGICAL UNIVERSITY DELFT
DEPARTMENT OF AERONAUTICAL ENGINEERING

Report VTH-136

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Dr. ir. O. H. Gerlach

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Errata

Front cover	line 10 should read: "February 1966".
page 16	Table 3, third column A_{z_o} should read: " A_{z_o} g".
page 23	lines 13 and 14 should read: "positions of the neutral point and the manoeuvre point and the various dynamic transferfunctions might have been calculated as well."
Fig. 12b	The values of C_Z on the left hand side of the graph should read, from bottom to top: "-0,6, -0,8, -1,0 and -1,2."
Fig. 12i	The values of $\frac{P}{\frac{1}{2}\rho V^3}$ on the left hand side of the graph should read from bottom to top: "0,020, 0,028 and 0,036".

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Measurements of performance, stability and control characteristics in non-steady flight with a high-accuracy instrumentation system

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Dr. ir. O.H.Gerlach [1)]

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Summary.

The paper deals with experiments to test a method for determining aircraft performance, stability- and control characteristics from measurements in non-steady flight. The instrumentation system used has been discussed in a previous paper, presented at the Third International Flight Test Instrumentation Symposium. The present paper discusses the method of analyzing the measured data. Some practical experience gained with the instrumentation system in the laboratory and in flight is described. Finally a check on the applicability of the method is made for a single-engine, propeller-driven aircraft.

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1. Introduction.

This paper may be considered as a continuation of a paper presented in 1964 at the Third International Flight Test Instrumentation Symposium, Ref.1. The subject of the discussions in both papers is a new flight test method, based on high-accuracy measurements in non-steady flight.

Whereas Ref. 1 contained a description of the instrumentation system developed for the flight test method, the present paper starts with a discussion of some theoretical aspects of the method. In particular two subjects will be dealt with: firstly the method of regression analysis, which forms the backbone of the flight test method and secondly the numerical method used to calculate the angle of attack during a non-steady manoeuvre.

As regards the results of experiments to be presented, two laboratory experiments will be discussed first. These tests were made to evaluate the accuracy to be obtained with the instrumentation system under favourable conditions. Thereafter flight test were made. The results of these tests, however, have yet not been fully analyzed at the present time. The discussion of the flight test results therefore has to be somewhat less complete than might be desirable. Finally a short review of some experience obtained so far, will be given.

In order to provide a yardstick against which the results of the flight test method can be measured, it is thought useful to repeat here what has been said in Ref. 1 about the aims of the method.

> "Restricting the method to symmetric flight, it might be possible to derive in an ideal case, from measurements during one non-steady manoeuvre, the aircraft characteristics indicated in Table 1, pertaining to the aircraft configuration as used in the manoeuvre and to the ranges of airspeed and angle of attack covered during the manoeuvre."

Table 1. Aircraft characteristics to be determined from measurements in non-steady flight.

1. Rate of climb in steady flight, as a function of airspeed.
2. Polar curve, C_L vs. C_D.
3. Elevator angle to trim in steady flight, as a function of airspeed.

4. Stick displacement per"g"in manoeuvring flight.
5. Longitudinal stability derivatives, including those with respect to change of airspeed.

2. Some theoretical aspects of the flight test method.

2.1. The method of regressionanalysis.

a. Equations of motion of the aircraft.

Analysis of the flight measurements is based on the non-linearized equations for the symmetric motions of a rigid aircraft, Fig. 1:

$$\begin{aligned} -W \sin \Theta + X &= m(\dot{u} + wq) \\ W \cos \Theta + Z &= m(\dot{w} - uq) \\ M &= I_y . \dot{q} \end{aligned} \qquad (1)$$

In these equations, X and Z are the total aerodynamic forces along the body-fixed X- and Z-axes and M is the total aerodynamic moment about the Y-axis.

As can be seen from Fig. 1, X and Z are composed of contributions from the lift L, the drag D and the thrust T_p. Specially important is the fact that an accelerometer having its sensitive axis along the X- or Z-axis, senses precisely the component X or Z of the total aerodynamic force R along that axis.

If A_x and A_z are the "specific forces" indicated by the two accelerometers, then:

$$A_x = \frac{X}{m} \qquad (2)$$

$$A_z = \frac{Z}{m} \qquad (3)$$

where m is the mass of the aircraft, as in (1). In this respect there is a direct parallel with the aerodynamic moment M, which follows from the angular acceleration:

$$\dot{q} = \frac{M}{I_y} \qquad (4)$$

Using (2) and (3) the aerodynamic forces X and Z can be derived from the specific forces A_x and A_z measured in flight. To obtain the aerodynamic moment M from (4), the angular velocity q is differentiated digitally when analyzing the data. The polar moment of inertia I_y of the aircraft has to be determined separately, preferably from experiments.

b. Aerodynamic coefficients.

The three aerodynamic quantities X, Z and M will now be considered in more detail, taking the longitudinal force X as an example. From Fig.1 follows:

$$X = T_p \cos i_p + L \sin \alpha - D \cos \alpha$$

Dividing by $\frac{1}{2}\rho V^2 S$:

$$C_X = T_c \cos i_p + C_L \sin \alpha - C_D \cos \alpha \tag{5}$$

A parabolic polar curve (C_D vs. C_L) is assumed:

$$C_D = C_{D_1} + \frac{(C_L - C_{L_1})^2}{\pi A e} \tag{6}$$

where:

$$C_L = C_{L_\alpha}(\alpha - \alpha_o) \tag{7}$$

Substituting (6) and (7) in (5) yields after some rearrangement:

$$C_X = C_{X_o}' + \frac{\partial C_X}{\partial T_c} \cdot T_c + \frac{\partial C_X}{\partial \alpha} \cdot \alpha + \frac{\partial C_X}{\partial \alpha^2} \cdot \alpha^2$$

or:

$$C_X = C_{X_o}' + C_{X_{T_c}} . T_c + C_{X_\alpha} . \alpha + C_{X_{\alpha^2}} . \alpha^2 . \tag{8}$$

Terms in (8) containing powers of α higher than the second have been neglected. In (8) C_X, T_c, α and α^2 are the variables derived from flight measurements. The constant C_{X_o}' and the partial derivatives $C_{X_{T_c}}$, C_{X_α}

and $C_{X_{\alpha^2}}$ have to be determined from the measurements by subsequent analyses.

Direct measurement of the propulsive thrust T_p or the thrustcoefficient T_c is rather difficult. Therefore, an auxiliary variable is introduced. This is the pressure ratio $\frac{\Delta p_t}{\frac{1}{2}\rho V^2}$, where Δp_t is the increase in total pressure at a somewhat arbitrary point in the slipstream:

$$\Delta p_t = p_{t_s} - p_t$$

In order to avoid variations in p_{t_s} due to sideslip and angle of attack effects, p_{t_s} is actually measured at two diametrically opposite points in the slipstream, Fig. 2.

The assumed relation between $\frac{p_t}{\frac{1}{2}\rho V^2}$ and T_c can be written as:

$$\frac{\Delta p_t}{\frac{1}{2}\rho V^2} = a + d.T_c \tag{9}$$

where a and d are constants. This expression should be valid for the rather limited range of T_c values encountered in one manoeuvre at a constant power setting.

Replacing T_c by $\frac{\Delta p_t}{\frac{1}{2}\rho V^2}$ in C_X by means of (9) yields:

$$C_X = C_{X_o} + C_{X_{\Delta p_t}} \cdot \frac{\Delta p_t}{\frac{1}{2}\rho V^2} + C_{X_\alpha}.\alpha + C_{X_{\alpha^2}}.\alpha^2 \tag{10}$$

Finally assuming propeller efficiency to be reasonably constant during the manoeuvre, (9) can be written as:

$$\frac{\Delta p_t}{\frac{1}{2}\rho V^2} = a + b \cdot \frac{P}{\frac{1}{2}\rho V^3} \tag{11}$$

where a and b are constants and P is the engine power. Provided a and b are known, (11) permits $\frac{\Delta p_t}{\frac{1}{2}\rho V^2}$ to be calculated for a given airspeed, altitude and engine power.

It may be noted that in the expression (10) for C_X, the variable $\frac{P}{\frac{1}{2}\rho V^3}$ could have been used instead of $\frac{\Delta p_t}{\frac{1}{2}\rho V^2}$, to replace T_c. The point in using $\frac{\Delta p_t}{\frac{1}{2}\rho V^2}$ lies in the fact that any fine variations in thrust affecting C_X should be more directly apparent from corresponding variations in $\frac{\Delta p_t}{\frac{1}{2}\rho V^2}$ than in $\frac{P}{\frac{1}{2}\rho V^3}$.

In a manner similar to the one shown for C_X, expressions for C_Z and C_m can be derived:

$$C_Z = C_{Z_o} + C_{Z_{\Delta p_t}} \cdot \frac{\Delta p_t}{\frac{1}{2}\rho V^2} + C_{Z_\alpha} . \alpha + C_{Z_q} \cdot \frac{q\bar{c}}{V} + C_{Z_\delta} . \delta_e \qquad (12)$$

$$C_m = C_{m_o} + C_{m_{\Delta p_t}} \cdot \frac{\Delta p_t}{\frac{1}{2}\rho V^2} + C_{m_\alpha} . \alpha + C_{m_{\dot\alpha}} \cdot \frac{\dot\alpha\bar{c}}{V} + C_{m_\delta} . \delta_e \qquad (13)$$

The terms proportional to $\frac{\dot\alpha\bar{c}}{V}$, $\frac{q\bar{c}}{V}$ and δ_e as introduced in C_Z and C_m will be well-known to those familiar with the theory of the dynamic stability of aircraft. Quite often the terms $C_{Z_{\Delta p_t}} \cdot \frac{\Delta p_t}{\frac{1}{2}\rho V^2}$ and $C_{Z_q} \cdot \frac{q\bar{c}}{V}$ in C_Z may be neglected. For many aircraft the centre of action of the force $C_{Z_\delta} . \delta_e$ due to elevator deflection can be estimated with some accuracy from geometric data. Assuming this point to be at a known distance ℓ_h behind the aircraft's centre of gravity, C_{Z_δ} is found from the moment derivative C_{m_δ} by:

$$C_{Z_\delta} = C_{m_\delta} \cdot \frac{\bar{c}}{\ell_h}$$

The above expressions (10), (12), (13) and (11) for C_X, C_Z, C_m and $\frac{\Delta p_t}{\frac{1}{2}\rho V^2}$ represent the mathematical model for the aerodynamic behaviour of the aircraft during a test manoeuvre. The variables C_X, C_Z, C_m, $\frac{\Delta p_t}{\frac{1}{2}\rho V^2}$, α, $\frac{\dot\alpha\bar{c}}{V}$, $\frac{q\bar{c}}{V}$, δ_e and $\frac{P}{\frac{1}{2}\rho V^3}$ have to be measured during the manoeuvre. From these measurements the constants C_{X_o}, C_{Z_o}, C_{m_o} and a and the partial derivatives

$C_{X_{\Delta p_t}}$, C_{X_α}, $C_{X_{\alpha^2}}$, $C_{Z_{\Delta p_t}}$ etc. have to be determined.

Assuming now for a moment that this part of the analysis has been completed, the data mentioned in Table 1, such as rate of climb, trim curve etc. can all be computed quite easily. These calculations are not discussed here.

c. Regression analysis.

The problem to be considered next, however, is how to find the unknown constants and partial derivatives in the expressions for C_X, C_Z, C_m and $\frac{\Delta p_t}{\frac{1}{2}\rho V^2}$. The method used to solve this problem is the so called regression analysis, which is based on the least squares principle, Ref. 2,3,4. As has been mentioned in Ref. 1, this method is also used to express the calibration curves of the instruments in a polynominal form. Because of the extensive use being made of regression analyses in this context, a discussion of the method seems appropriate.

The previous expressions for C_X, C_Z, C_m and $\frac{\Delta p_t}{\frac{1}{2}\rho V^2}$ can be written in a general from:

$$Y = a_o + a_1X_1 + a_2X_2 + \ldots\ldots + a_mX_m \tag{14}$$

where Y and X_i (i = 1, ..., m) now are the known, measured variables and the so called regressioncoefficients a_i (i = 0,1, ..., m) are the quantities to be determined. It is assumed that n different groups of values of Y and X_i - each group pertaining to a certain instant in time - are available, where n $\gg$ m. In the examples to be discussed later, n may be approximately 150, whereas m is not greater than 5.

The least squares principle requires that the coefficients a_i be chosen in such a way that:

$$S = \sum_n \left\{ Y - (a_o + a_1X_1 + \ldots. + a_mX_m) \right\}^2 = \min \tag{15}$$

Therefore:

$$\frac{\partial S}{\partial a_o} = 0 \tag{16}$$

and:

$$\frac{\partial S}{\partial a_1} = 0, \; \ldots\ldots\ldots\ldots, \; \frac{\partial S}{\partial a_m} = 0 \qquad (17)$$

In the actual computation of the regressioncoefficients a_i a simplification is obtained by subtracting from each variable its average value:

$$y = Y - \overline{Y}$$

$$x_i = X_i - \overline{X}_i$$

From (16) follows quite easily:

$$a_o = \overline{Y} - (a_1\overline{X}_1 + \ldots\ldots + a_m\overline{X}_m)$$

This means that a_o can be found as soon as the remaining $a_i (i=1,\ldots,m)$ are known.

The general expression (14) can now be written as:

$$y = a_1x_1 + \ldots. + a_mx_m$$

It is of interest to consider the deviation Δy:

$$\Delta y = y - (a_1x_1 + \ldots\ldots. + a_mx_m)$$

$$= Y - (a_o+a_1X_1 + \ldots. + a_mX_m)$$

Using this deviation, the sum S to be minimized according to (15) is:

$$S = \sum_n \Delta y^2$$

If the measured data fit the expression (14) exactly, the result is:

$$\Delta y \equiv 0$$

The quality of the adaptation of the formula (14) to the measured data is expressed by a so called total correlationcoefficient R, defined by:

$$R^2 = 1 - \frac{\sum \Delta y^2}{\sum y^2} \qquad (R \geqslant 0)$$

In the ideal case, when $\Delta y \equiv 0$, R attains its maximum value: R = 1. If the data do not fit the formula at all, R is at its minimum: R = 0. Some typical values of R obtained when applying regression analyses to instrument calibrations and flight manoeuvres are given in Table 2.

Table 2. Values of total correlationcoefficients R.

Application	R
Calibration of rate of pitch gyro	0.999 999 95
Calibration of accelerometer	0.999 999 5
Calibration of pressure transducer	0.999 995
Expressions for C_X, C_Z, C_m or $\frac{\Delta p_t}{\frac{1}{2}\rho V^2}$	0.995

If a given set of data points is fitted to several different expressions of the type (14), the total correlationcoefficient indicates which of these expressions provides the best fit to the given data. As a practical example, it is often desirable to know whether the inclusion in the expression (14) of a new variable X_j having a small influence on Y actually improves the mathematical representation of the given data. The total correlationcoefficient may provide an answer to such a question.

All actual calculations are performed on a digital computer. But not only the regressioncoefficients are provided by solving the equations (16) and (17). The value of R will be computed as well and it is also quite useful to have the computer prepare a list of the n deviations Δy. If by chance an error has crept into the measured data, a low value of R may at once give an indication of such an occurance. Usually the list of deviations shows the exact location of the error.

Regression analysis can provide still more information on the quality of the measurements. For instance some idea of the probable error in the regressioncoefficients a_i can be obtained.

To explain this point, let us suppose we try to describe the variations of X_1 about its average value $\overline{X}_1$ by the linear expression:

$$x_1 = b_{12}.x_2 + \ldots\ldots b_{1m}.x_m \tag{18}$$

The "best" values of b_{12}, ..., b_{1m} can again be determined on a least squares basis. Usually the expression (18) is not all true. Therefore, the deviations

$$\Delta x_1 = x_1 - (b_{12}.x_2 + \ldots\ldots + b_{1m}.x_n)$$

are not nearly equal to zero for all n data points. Like the total correlationcoefficient R, a partial correlationcoefficient R_1 can now be defined:

$$R_1^{\ 2} = 1 - \frac{\Sigma \Delta x_1^{\ 2}}{\Sigma x_1^{\ 2}} \qquad 0 \leqslant R_1 \leqslant 1$$

The value of R_1 indicates the extent to which x_1 is a linear function of the other variables $x_i(i=2,\ldots.,m)$. $R_1=1$ corresponds to a perfect linear relationship.

The importance of the partial correlationcoefficient can be seen from the following. It can be proved that, under certain rather restrictive conditions, see Ref. 2,3,4, the variance of the regression-coefficient a_1, if it could be determined many times from a great number of sets of data points, each set consisting of n points, is given by:

$$\sigma_{a_1}^{\ 2} = \frac{1}{n-m-1} \cdot \frac{\Sigma \Delta y^2}{\Sigma \Delta x_1^{\ 2}} = \frac{1}{n-m-1} \cdot \frac{\Sigma y^2(1-R^2)}{\Sigma x_1^{\ 2}(1-R_1^{\ 2})} \tag{19}$$

In the same way as R_1, a partial correlationcoefficient R_2 can be introduced by letting:

$$x_2 = b_{21}x_1 + b_{23}x_3 + \ldots\ldots + b_{2m}.x_m$$

and:

$$\Delta x_2 = x_2 - (b_{21}.x_1 + b_{23}.x_3 + \ldots\ldots + b_{2m}.x_m)$$

Then the partial correlationcoefficient R_2 is defined by:

$$R_2^2 = 1 - \frac{\sum \Delta x_2^2}{\sum x_2^2} \qquad 0 \leq R_2 \leq 1$$

The variance of a_2 then is:

$$\sigma_{a_2}^2 = \frac{1}{n-m-1} \cdot \frac{\sum \Delta y^2}{\sum \Delta x_2^2} = \frac{1}{n-m-1} \cdot \frac{\sum y^2 .(1-R^2)}{\sum x_2^2 .(1-R_2^2)} \qquad (20)$$

It will be clear that for each of the m variables X_i a partial correlationcoefficient R_i can be defined. The variances of the regressioncoefficients $a_i (i=1,....,m)$ are given by expressions like (19) and (20).

Finally the variance of a_o can be written as

$$\sigma_{a_o}^2 = \frac{1}{n-m-1} \cdot \sum \Delta y^2 = \frac{1}{n-m-1} \cdot \sum y^2 .(1-R^2)$$

d. Interpretation of the correlationcoefficients.

The meaning of the correlationcoefficients introduced in the previous paragraph may be illustrated by the following remarks.

Accurate results of the measurements - as indicated by small values of $\sigma_{a_i}^2$ - require accurate measurements and a good mathematical model, in order to obtain a high value of R. An equally important but less evident requirement, however, says that the partial correlationcoefficients R_i shall be as low as possible.

This second requirement simply means, that none of the variables X_i is allowed to be a linear function of some or all of the other variables X_i. The less the variables are linearly dependent, the higher is the accuracy with which the regression coefficients can be obtained from measurements of a given accuracy.

In this connection the introduction of a new variable X_j into the expression (14) has to be mentioned again. It may well be that its inclusion increases the total correlationcoefficient R, indicating a better fit of the mathematical model to the measured data. Quite often, however, the new variable causes the variables $X_i(i=1,.....,m+1)$ to be more linearly related, as evidenced by an increase in some or all of the partial correlationcoefficients. The result is a reduction in the accuracy of the regression coefficients a_i, indicated by an increase in the variances $\sigma_{a_i}^2$. In such a situation it may be preferable to choose a less complete mathematical model for the measured data, thereby improving the accuracy with which the remaining coefficients a_i can be determined.

When applying the foregoing to flight measurements, the different X_i represent the variables α, $\frac{\dot{\alpha}\bar{c}}{V}$, $\frac{q\bar{c}}{V}$ etc. Unfortunately it is not possible to vary these components of the aircraft's motions entirely independent from one another. The equations of motion of the aircraft mentioned earlier determine how the changes in the different variables are related.

Some influence, however, can be exerted on the magnitude of the partial correlationcoefficients, by making a judicious choice of the elevator deflection as a function of time.

To study this subject further, see Ref. 5, two manoeuvres were simulated digitally. The different variables in these manoeuvres were used as if they had been obtained from actual flight measurements. The data were mutilated in various ways to simulate measurement errors. Applying regression analyses to these "measured" data, the regression coefficients a_i were found which could be compared to their exact values as used in the initial calculation of the manoeuvre.

In this study it was found that the expressions for the variances $\sigma_{a_i}^2$ do not hold too well quantitatively, especially not if the correlationcoefficients R and R_i do not differ very much in magnitude. Nevertheless it became quite clear that the accuracy of the regression coefficients strongly depends on the magnitude of the partial correlationcoefficients. It appears then, that every effort should be made to perform a manoeuvre which results in the lowest possible values of R_i. This holds specially true for those expressions (14) where Y is a function of many variables X_i, as is the case for the aerodynamic moment C_m. The form of the manoeuvre finally chosen in Ref. 5 bearing this idea in mind is shown in Fig. 3.

2.2. A method to determine the angle of attack in a non-steady manoeuvre.

The quality of some instruments used in the instrumentation system is such as to suggest a somewhat unorthodox method to determine the angle of attack α during a non-steady manoeuvre. Actually, angle of pitch Θ, rate of climb $\dot{h}$ and flight path angle γ are obtained as well. The method may be characterized very briefly as follows.

The angle of attack α is found as the difference between the angle of pitch and the flight path angle. The former angle can be obtained by integrating rate of pitch, the latter is determined from the horizontal and the vertical components of the aircraft's velocity vector. These two velocity components are derived by integrating the horizontal and vertical accelerations. Integrating the vertical acceleration twice yields the vertical displacement or change of height. Now the horizontal velocity as well as the change of height can also be obtained from pressure measurements. This redundancy in the data available offers the possibility to correct for a few errors in the velocity components found from integrations.

The method appears to have a few advantages over more conventional methods to determine the same variables:

1. an internal check on the accuracy of the instruments is obtained,
2. no separate instrument is needed to measure the angle of attack,
3. the rather time-consuming calibration in flight of an angle of attack indicator is eliminated.

This section contains a description of the method. From Fig. 4 follow expressions for the horizontal and vertical accelerations:

$$
\begin{aligned}
a_{hor} &= A_x \cos \Theta + A_z \sin \Theta \\
a_{vert} &= A_x \sin \Theta - A_z \cos \Theta - g
\end{aligned}
\qquad (21)
$$

where Θ is found by integrating $\dot{\Theta}$, as indicated in Ref. 1:

$$\Theta = \Theta(o) \int_o^t (q \cos \varphi - r \sin \varphi)dt$$

Integrating a_{hor} once yields the change in change in horizontal velocity U:

$$U(t) - U(o) = \int_o^t (A_x \cos \Theta + A_z \sin \Theta)dt \qquad (22)$$

Also, the rate of climb and the change in height are obtained by integrating a_{vert}:

$$\dot{h}(t) = \dot{h}(o) + \int_o^t (A_x \sin \Theta - A_z \cos \Theta - g)dt$$

$$h(t) - h(o) = \dot{h}(o).t + \iint_o^t (A_x \sin \Theta - A_z \cos \Theta - g)dt^2 \qquad (23)$$

In flight, the change in horizontal velocity and the change in height can be deduced rather accurately from pressure measurements. It is estimated that changes in the velocity occurring over an interval of 30 - 60 sec. at a level of about 60 m/sec. can be obtained in quasi-steady flight with a possible error not greater than 0.1 m/sec., whereas changes in height over the same interval can be determined as accurately as 0.1 m.

Now U(t) - U(o) as well as $\Delta h = h(t) - h(o)$ can be found in two entirely different ways. They can be determined by integration according to (22) and (23) and also from pressure measurements. In an ideal case the two methods should give identical results. The differences in results occurring when using actual measurements may be ascribed to certain sources of errors, known - or thought to be known - beforehand. The principal sources of errors in the determination of a_{hor} and a_{vert} are:

1. An error in $\Theta(o)$: $\Delta\Theta(o)$
2. a zero-shift in the calibration - formula of the rate of pitch gyro: Δq_o
3. an error in the initial rate of climb: $\Delta\dot{h}(o)$
4. a zero-shift in the calibration-formula of the Z-accelerometer: ΔA_{z_o}.

It is possible then, to construct an "error-model", relating the error in the change of horizontal velocity $\Delta U(t)$ and the error in the change of height $\Delta\Delta h(t)$ to the four sources of errors listed above. This error-model is expressed by:

$$\Delta U(t) = -\Delta\Theta(o).\int_o^t (-A_x \sin\Theta + A_z \cos\Theta)dt - \Delta q_o \int_o^t (-A_x \sin\Theta + A_z \cos\Theta)t\,dt \qquad (24)$$

$$\Delta\Delta h(t) = \Delta\dot{h}(o).t - \Delta\Theta(o).\iint_o^t (A_x \cos\Theta + A_z \sin\Theta)dt^2 +$$

$$-\Delta q_o \iint_o^t (A_x \cos\Theta + A_z \sin\Theta)t\,dt^2 + \Delta A_{z_o} \iint_o^t \cos\Theta\,dt^2 \qquad (25)$$

Considering $U(t) - U(o)$ and $\Delta h(t)$ as found from pressure measurements as the exact values, the errors $\Delta U(t)$ and $\Delta\Delta h(t)$ can be found by comparing the exact values with those computed from (22) and (23). The variable coefficients of $\Delta\Theta(o)$, Δq_o, $\Delta\dot{h}(o)$ and ΔA_{z_o} in (24) and (25) also are obtained quite easily from the measurements, using the digital computer. Applying the technique of regression analysis once more to (24) and (25), it is a straightforward matter to determine the unknown $\Delta\Theta(o)$ and Δq_o from (24) and $\Delta\dot{h}(o)$ and ΔA_{z_o} from (25).

Improved values of $q(t)$, $\Theta(t)$ and $\dot{h}(t)$ are then obtained by applying the corrections just found to the measured data. Finally the angle of attack α is computed from:

$$\alpha = \Theta - \text{arc tg}\,\frac{\dot{h}}{U} \qquad (26)$$

3. Results of experiments.

3.1. Introduction.

This part of the paper contains the discussion of some results as obtained by applying the foregoing theory to measurements with the instrumentation system described in Ref. 1. It may be useful here to mention briefly a few particulars of the instrumentation system, Fig.5.

It contains some 15 transducers which are scanned according to a fixed program at a rate of 80 points per sec. The entire scanning cycle consisting of 192 measurements, lasting 2.4 sec. The highest sampling rate used for a single instrument is 10x per sec, the lowest is once per 2.4 sec. All transducer outputs are DC voltages in the range of 0-10 V. These voltages are filtered and then converted by a digital voltmeter into a 4 decade BCD number. The accuracy of the digital voltmeter is 0.01°/o of full range ± 1 bit. Recording is done on magnetic tape. All analyses of recorded data are performed on a high-speed digital computer.

3.2. Laboratory tests.

a. Tests on an oscillating table.

In order to test the theory described in section 2.2 on the determination of the angle of attack, a few experiments were made in the laboratory.

The accelerometers and rate gyro's of the instrumentation system were mounted on a rigid boom, extending about 2 m from the axis of an oscillating table. The table was oscillated approximately like the aircraft during a manoeuvre in flight. During the oscillations, lasting about 25 sec., all output signals from the instrumentation were recorded. Also the angle of tilt of the table was recorded by means of the transducer normally used in the instrumentation system to measure the elevator angle of the aircraft in flight. Fig. 6 shows to the left the instrumentation system and to the right the oscillating table with the boom carrying the instruments.

The "exact" horizontal velocity of the accelerometers and gyro's as well as the height above a reference level were calculated from the angle of tilt of the table and from the distances of the instruments to the axis of rotation. These exact values could then be compared with those found by integrating A_x, A_z and θ, according to (21), (22), and (23). Using the error-model (24) and (25), values of $\Delta\theta(o)$, Δq_o, $\Delta\dot{h}(o)$ and ΔA_{z_o} were found.

If the sources of errors allowed for in the error-model are indeed the only ones present in the experiment, the changes in horizontal velocity and height found by integrating the corrected values of a_{hor}, a_{vert} and $\dot{h}(o)$ should be identical to the "exact" values. Fig. 7 presents some results of these laboratory experiments. Fig. 7a shows the rate of pitch q during the manoeuvre. From Fig. 7b and c it can be seen that the errors in the change in horizontal velocity and in height before applying any corrections amount to 1,4 m/sec (4.6 ft/sec) and 1,5 m (4.9 ft) respectively after 26 sec. Finally, Fig. 7d and e indicate that these errors are reduced to not more than approximately 0,002 m/sec (0.007 ft/sec) and 0,004 m (0.013 ft) respectively by applying the corrections found from the error model. The r.m.s. values of the remaining errors are: $\sqrt{\overline{\Delta\theta}^2} = 0.055^o$, $\sqrt{\overline{\Delta U}^2} = 0.0012$ m/sec (0.0039 ft/sec) and $\sqrt{\overline{\Delta\Delta h}^2} = 0.0021$ m (0.0069 ft).

Four of these manoeuvres were recorded and all yielded similar results. In particular the instrument errors Δq_o and ΔA_{z_o} were found to repeat very well, see Table 3.

Table 3. Instrument errors Δq_o and ΔA_{z_o} as found from tests on an oscillating table

Manoeuvre	Δq_o ^{o}/sec	ΔA_{z_o}
1	-0,0242	-0.000440
2	-0,0237	-0.000436
3	-0,0242	-0.000502
4	-0,0226	-0.000475

b. Tests in the lift-cage of a tall building.

The determination of angle of attack according to the intended method requires the accurate measurement of the change of height during a flight manoeuvre. To satisfy this requirement a special instrument was developed, see Ref. 1. In order to facilitate the understanding of the following, a brief summary of the principle of operation of this instrument is thought useful here.

The main components are a sensitive differential pressure gauge and a thermosflask, Fig. 8a. When the interior of the thermosflask is shut off from the atmosphere, the pressure gauge becomes sensitive to changes in atmospheric pressure, the pressure of the air enclosed in the flask serving as a reference level. In order to avoid overstressing of the pressure gauge due to too large changes in height, the entire system consists of two identical halves Fig. 8b. During most of the time only one halve is in operation, or active, while the other one is passive. When the active part approaches the limits of its range, due to prolonged ascending or descending of the aircraft, the other part is brought into action, as well. During a few tenths of a second both halves operate simultaneously, measuring the same changes in atmospheric pressure. Thereafter, the up to then active part is brought to rest and the active role is taken over entirely by the second halve. The action of switching the two parts at the correct instants has been made fully automatic. It may be mentioned in passing that, as the result of flight measurements, the range of the differential pressure gauges has been increased to $\pm$ 5 mbar, as opposed to the $\pm$ 2 mbar mentioned in Ref. 1.

The analysis of the recorded pressures is somewhat more complicated than may appear at first sight. This is due to the fact that every pressure change in the thermosflasks is accompanied by a change in air temperature, caused by the slight expansion or compression of the air. The contact of the air with the wall of the flask, however, causes the air temperature to return to its original value in due time. The variation in air temperature due to the heat exchange with the flask continues even when the flask has been shut off from the atmosphere. The changing air temperature in this situation causes the pressure in the flask to vary. As it is precisely this pressure that serves as a reference in measuring the changes of atmospheric pressure, the desired accuracy of the system can only be attained if these temperature effects are fully corrected for in the analysis of the measurements. A brief calculation shows that an uncorrected variation of only 0.003^{o}C in the air temperature inside the flask causes an error in height of about 0.1 m at low altitudes.

It has been tried out experimentally how far these temperature corrections can be succesfully applied. To this end it was necessary to change the altitude of the entire instrumentation system sufficiently to bring both parts of the pressure system into operation one after another. Yet the vertical displacements had to be measured with an accuracy an order of magnitude better than the hoped for accuracy of the pressure measuring system, leaving an allowable error of a few cm's only.

These requirements could be satisfied quite well, using a lift in the building of the Department of Aeronautics of the Technological University at Delft. The vertical displacement possible with the lift is about 48 m (160 ft).

In order to simplify the tests, no measurements of the cage altitude were made. Only when the lift-cage had stopped, the exact altitude was known. When the doors of the lift had opened, the pressure in the cage could be assumed to be equal to the static pressure at that height. The tests were made, still using the pressure gauges with a range of ± 2 mbar.

Several runs have been recorded. Fig. 9 shows the results of one of these. The particular motion the cage went throught has been indicated in Fig. 9a. The total change in height was such that switching between the two halves of the pressure measuring system occurred twice. It can be seen from Fig. 9b that during those parts of the recording period where the height was constant, the error in height determined from the pressure measurements generally was within 0.1 m. Also it may be noted that this accuracy was obtained over an interval in time lasting about 100 sec, which is more than twice the duration of a flight manoeuvre.

3.3. Measurements in flight.

a. Determination of the angle of attack.

Turning to flight measurements now, two different sets of results will be discussed. The first of these bears on the determination of the angle of attack during a manoeuvre.

Fig. 10 presents the results of a recording made in nearly steady, level flight. The analysis of these measurements was performed according to the theory described in section 2.2. By integrating rate of pitch, vertical and horizontal accelerations, it was tried to duplicate the changes of altitude Δh and horizontal velocity U, derived from pressure measurements. The initial values of angle of pitch $\Theta(o)$ and rate of climb $\dot{h}(o)$ as well as the zero-shifts Δq_o and ΔA_{z_o} were adjusted to this end. Fig. 10 shows the results of this procedure. The r.m.s. values of the remaining errors ΔU and $\Delta\Delta h$ are 0.058 m/sec (0.19 ft/sec) and 0.078 m (0.26 ft) respectively. The effect of imperfections in the pressure measurements is also included in these figures. It may, therefore, be concluded that small changes in pressure-derived altitude and airspeed can be matched very well by inertial measurements in nearly steady, level flight. The time-history of the angle of attack following from these measurements, according to (26), is shown in Fig. 10e.

The results are not yet so favourable if a non-steady manoeuvre is analyzed, see Fig. 11. The changes of horizontal speed and height to be matched by the inertial measurements now are somewhat larger, Fig. 11a and c, and so are the remaining errors ΔU and $\Delta\Delta h$, Fig. 11b and d. The r.m.s. values of ΔU and $\Delta\Delta h$ in this example are 0.12 m/sec (0.39 ft/sec) and 0.29 m (0.95 ft) respectively.

The exact causes for these errors have not yet been determined. From the results of several manoeuvres plotted in this way, it has become evident, however, that the general shape of these error-curves repeats quite systematically. In the $\Delta\Delta h$-t curve. Fig. 11d, the curve of A_z or C_Z against time may be recognized. It is expected, that a better knowledge of the underlying sources could eventually lead to a more complete elimination of these errors than is possible at the present time.

b. Results of regression analyses, based on flight measurements.

At the time of writing, a series of experiments has been completed recently. During 8 flights more than 200 manoeuvres were recorded. It is yet too early to present a complete picture of the results. Therefore, only some results obtained from one manoeuvre will be discussed here.

The variables of interest, as derived from the flight measurements, have been plotted in Fig.12. Using these variables a series of regression analyses was performed, according to the theory given in Section 2.1. It may be of interest to discuss some of the results of these regression analyses in more detail.

The measured variations of C_X were fitted to the expression:

$$C_X = C_{X_o} + C_{X_{\Delta p_t}} \cdot \frac{\Delta p_t}{\frac{1}{2}\rho V^2} + C_{X_\alpha}.\alpha + C_{X_{\alpha^2}}.\alpha^2 \qquad (10)$$

as mentioned in Section 2.1, and also to:

$$C_X = C_{X_o} + C_{X_{\Delta p_t}} \cdot \frac{\Delta p_t}{\frac{1}{2}\rho V^2} + C_{X_\alpha}.\alpha + C_{X_{\alpha^2}}.\alpha^2 + C_{X_{\dot\alpha}}.\frac{\dot\alpha \bar c}{V} \qquad (27)$$

in order to see whether a non-steady effect exists in the variations of C_X. This is a case where the effect of the addition of a small term - $C_{X_{\dot\alpha}} \cdot \frac{\dot\alpha \bar c}{V}$ in the expression for C_X - is considered. It turns out that the total correlationcoefficient hardly improves when the new term is added. R increases from 0.99868 to a new value 0.99875. The implication is that $\frac{\dot\alpha \bar c}{V}$ only has a very small influence on C_X. This fact is affirmed by the low value of the coefficient $C_{X_{\dot\alpha}}$ found. The partial correlation-coefficients do not change very much either. They have been given in Table 4.

Table 4. Partial correlationcoefficients of the variables in the expression (27) for C_X.

$R_{\Delta p_t}$	0.15870
R_α	0.98958
R_{α^2}	0.98965
$R_{\dot\alpha}$	0.50478

It follows from this Table, that $\frac{\dot\alpha \bar c}{V}$ has only a rather low linear correlation with $\Delta p_t/\frac{1}{2}\rho V^2$, α and α^2. This explains why the includion of $\frac{\dot\alpha \bar c}{V}$ in C_X does not degrade the determination of the other regression coefficients. These coefficients remain practically unchanged when the term $C_{X_{\dot{\alpha}}} \cdot \frac{\dot{\alpha}\bar{c}}{V}$ is added.

The deviations ΔC_X between the measured values of C_X and those predicted by the formula were also studied:

$$\Delta C_X = C_X - (C_{X_{\Delta p_t}} \cdot \frac{\Delta p_t}{\frac{1}{2}\rho V^2} + C_{X_\alpha}.\alpha + C_{X_{\alpha^2}}.\alpha^2 + C_{X_{\dot{\alpha}}} \cdot \frac{\dot{\alpha}\bar{c}}{V}) .$$

Fig. 13b presents the results obtained initially. It appears that ΔC_X does not vary randomly during the manoeuvre, but shows some resemblance to the variations of C_m, see Fig. 12. This similarity proved to be due to the fact that the X-accelerometer was mounted a small distance (0.25 m = 10 in.) below the aircraft's centre of gravity. The accelerometer therefore sensed to a very slight degree the aircraft's angular accelerations about the lateral axis. When this effect was corrected for, the deviations ΔC_X shown in Fig. 13c were obtained. This correction caused the total correlationcoefficient R to increase from 0.99653 to the value 0.99875 mentioned above.

Next the analysis of C_m will be considered. In Section 2.1 C_m has been written as:

$$C_m = C_{m_o} + C_{m_{\Delta p_t}} \cdot \frac{\Delta p_t}{\frac{1}{2}\rho V^2} + C_{m_\alpha}.\alpha + C_{m_{\dot{\alpha}}} \cdot \frac{\dot{\alpha}\bar{c}}{V} + C_{m_q} \cdot \frac{q\bar{c}}{V} + C_{m_\delta}.\delta_e \tag{13}$$

A regression analyses based on this expression yielded a total correlationcoefficient R = 0.99540. The partial correlationcoefficients turned out as shown in Table 5.

Table 5. Partial correlationcoefficients of the variables in the expression (13) for C_m

$R_{\Delta p_t}$	0.99053
R_α	0.99555
$R_{\dot{\alpha}}$	0.99681
R_q	0.99842
R_δ	0.96033

These partial correlationcoefficients are very high indeed. As a consequence the regressioncoefficients cannot be determined with some accuracy, as has been discussed in Section 2.1. The coefficients $C_{m_{\alpha}}$, $C_{m_{\dot{\alpha}}}$ and C_{m_q} are specially liable to great errors, because the corresponding partial correlationcoefficients are even higher than the total correlationcoefficient. This is just another confirmation of the well known fact that it is difficult to separate all stability derivatives in the expression for C_m.

When $\frac{\dot{\alpha}\bar{c}}{V}$ is deleted as an independent variable in C_m because it is so linearly related to α, $\frac{q\bar{c}}{V}$ and δ_e, the remaining regression coefficient can be determined much better. The expression for C_m now becomes:

$$C_m = C_{m_o}' + C_{m_{\Delta p_t}}' . \frac{\Delta p_t}{\frac{1}{2}\rho V^2} + C_{m_{\alpha}}' . \alpha + C_{m_q}' . \frac{q\bar{c}}{V} + C_{m_{\delta}}' . \delta_e \quad (28)$$

where the primes indicate that the numerical values of the coefficients are different from those in (13). The regression analysis based on (28) yielded a total correlation coefficient R = 0.99528, which is only very slightly lower than the value 0.99540 obtained from (13). The partial correlationcoefficients, however, show a substantial reduction, see Table 6.

Table 6. Partial correlationcoefficients of the variables in the expression (28) for C_m.

$R_{\Delta p_t}$	0.58047
R_{α}	0.75843
R_q	0.95123
R_{δ}	0.95734

It will be clear that the regression coefficients based on the simplified expression (28) for C_m have been used in further calculations.

When the various regression analyses were completed, the aircraft characteristics mentioned in Table 1 were calculated. These data, presented in Fig. 14, are the final results obtained from the manoeuvre.

As regards the aircraft's performance, rate of climb as a function of airspeed was derived, as well as the polar drag curve, see Fig. 14a and b. It should be emphasized that these data can be considered valid only within the ranges of airspeed and angle of attack used in the manoeuvre. Information on the static control characteristics is contained in the curves showing the elevator angle to trim in steady flight and the stick displacement per "g" in manoeuvring flight, see Fig. 14c and d. Finally the various stability derivatives, calculated from the regression coefficients, were used to obtain the period and damping of the two longitudinal modes of the aircraft, again as a function of airspeed, see Fig. 14e and f.

It may be clear that several other characteristics, such as the positions of the neutral point and the manoeuvrepoint and the various functions might have been calculated as well.

From the foregoing the impression may be gained, at least superficially, that the aims of the method set forth in Ref. 1 and summarized in Table 1 of this paper have indeed been obtained. The results just discussed, however, refer to not more than a single manoeuvre. Although they are backed up by similar results from a few other manoeuvres, they must still be considered as preliminary in several aspects. Only when the majority of the measurements now available have been analyzed, a somewhat balanced opinion on the flight test method can be given.

4. Review of experiences with the flight test method.

It may be useful to try to summarize here the experiences obtained so far with the flight test method under discussion.

Concerning the instrumentation system, the following few remarks can be made.

1. The system has proved to be remarkably reliable. Notwithstanding the relative delicacy of some of its components no more, or rather less, trouble was experienced as regards the serviceability of the system than with several simpler systems operated by the same team. The present system has been in the aircraft for several periods, each lasting a few months. Operating the system in flight was not unduly difficult. Most

flight recordings were obtained by students, in the course of their thesis work.

2. The most critical single factor affecting the accuracy of the output signals of the system has been the environmental temperature. For this reason nearly all transducers were contained in thermostatically controlled boxes. The filter networks were not treated in this way, their components were selected for their low temperature coefficients. Ageing of these components proved to have a critical effect on the static characteristics of the filters.

3. The "one-g" output of the Z-accelerometer and the zero-output of the rate of pitch gyro appeared to be rather different in flight from their respective values on the ground. Differences of 0.14 "g" and 0.03 ^{o}/sec were noted repeatedly. These differences may have been caused by vibration effects. No attempts have yet been made to see whether similar changes in the zero-outputs of the X- and Y-accelerometers occurred as well. This subject still needs further study.

At the time of writing final results of the flight test method are scarce. When considering the results as they apply to the De Havilland DHC-2 "Beaver" aircraft used for the tests, the following can be said.

1. From the limited data available now, it appears that the aims of the method set out in Ref. 1 may indeed be realized.

2. A strong impression has been obtained that the method of regression analysis, used to analyze the aerodynamic characteristics of the aircraft, is as effective to this end as has been found in the theoretical study of Ref. 5.

3. Very little indication can be given at the present time as regards the repeatability of the final results of the method. Also, their sensitivity to changes in the instrument calibration characteristics has not yet been determined. Several similar questions must remain unanswered until the results of further study become available.

4. Preparation of the computer programmes to be used for the analysis of the recorded data, is a major undertaking. In the analysis great attention has to be given to a variety of seemingly unimportant details, in order not to loose the high accuracy offered by the instrumentation

system.

Conclusions.

In this paper a progress-report has been given on a project, intended to develop a flight test method, centered around accurate measurements in non-steady flight. Work on this project has been reported earlier, at the Third International Flight Test Instrumentation Symposion.

It has been possible to reach some conclusions as regards the instrumentation system used. The experience gained, showed that it is practicable to work to the high instrument-accuracies envisaged when originating the project. Operating the instruments appears to be no more difficult than working with more conventional instrumentation systems used for flight test purposes.

As regards the results obtained when applying the flight test method to a particular aircraft, it seems to be too early yet to make definite statements. Some encouraging results have been obtained, but much more analysis of flight measurements has to be performed, before an attempt can be made to reach final conclusions.

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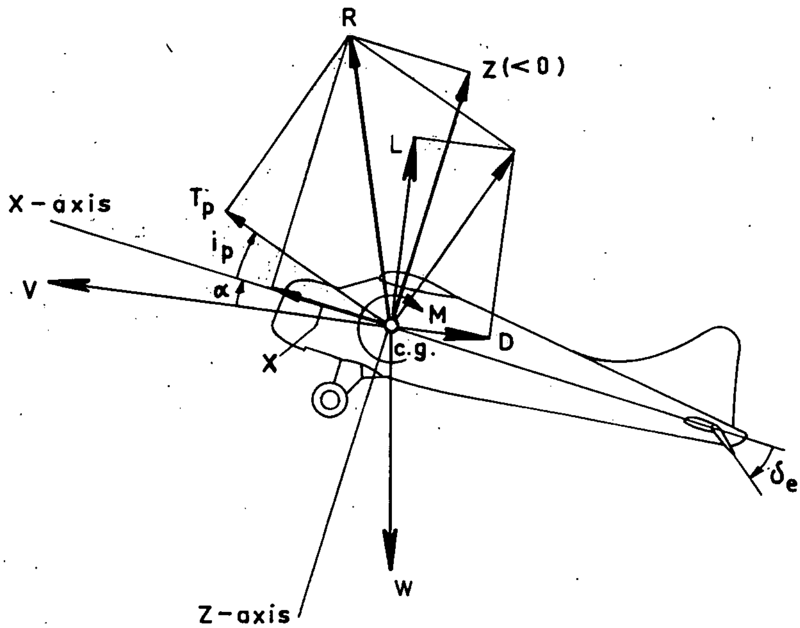


FIG. 1: THE FORCES AND MOMENTS ACTING ON AN AIRCRAFT IN SYMMETRIC FLIGHT.

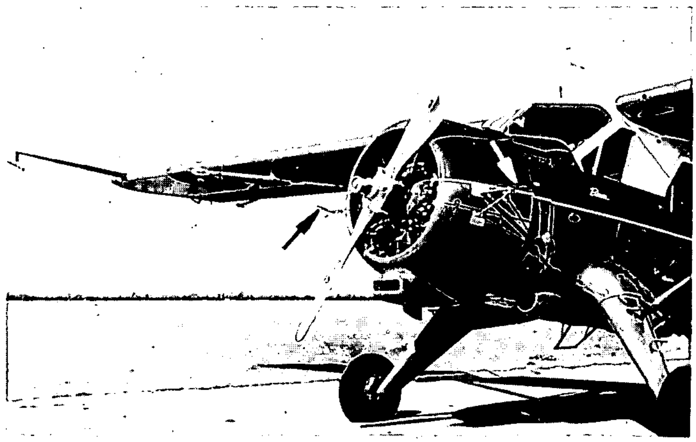


FIG. 2: MEASUREMENT OF THE TOTAL PRESSURE IN THE SLIPSTREAM p_{t_s}.

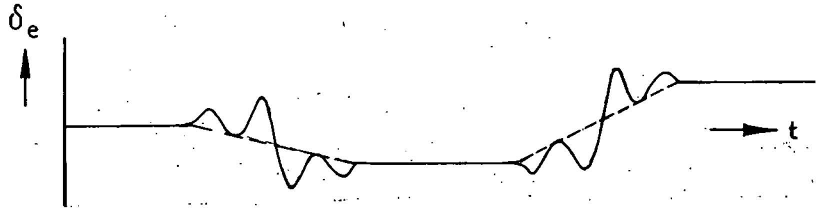


FIG. 3 : ELEVATOR ANGLE AS A FUNCTION OF TIME DURING A MANOEUVRE.

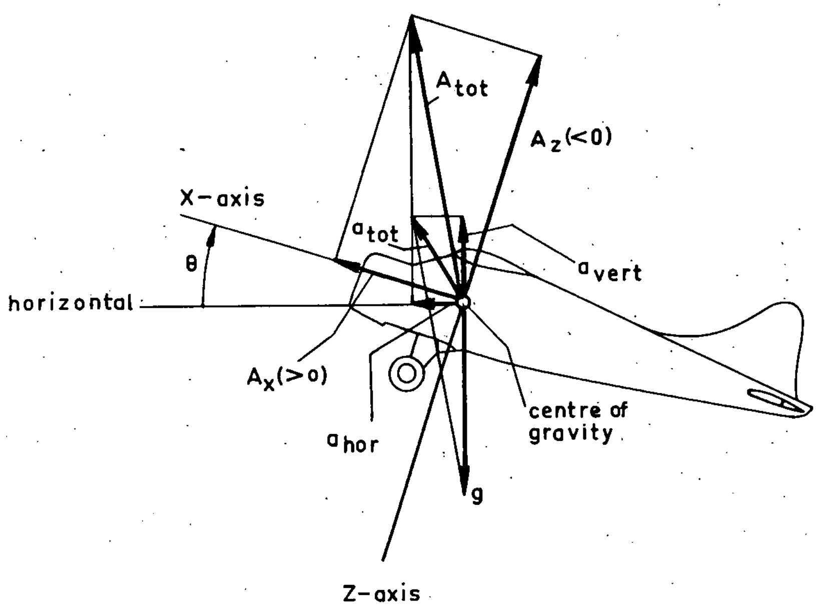


FIG. 4 : ACCELERATIONS a_{hor} AND a_{vert} OF THE AIRCRAFT IN THE PLANE OF SYMMETRY. A_x AND A_z ARE THE SPECIFIC FORCES AS SENSED BY THE ACCELEROMETERS.

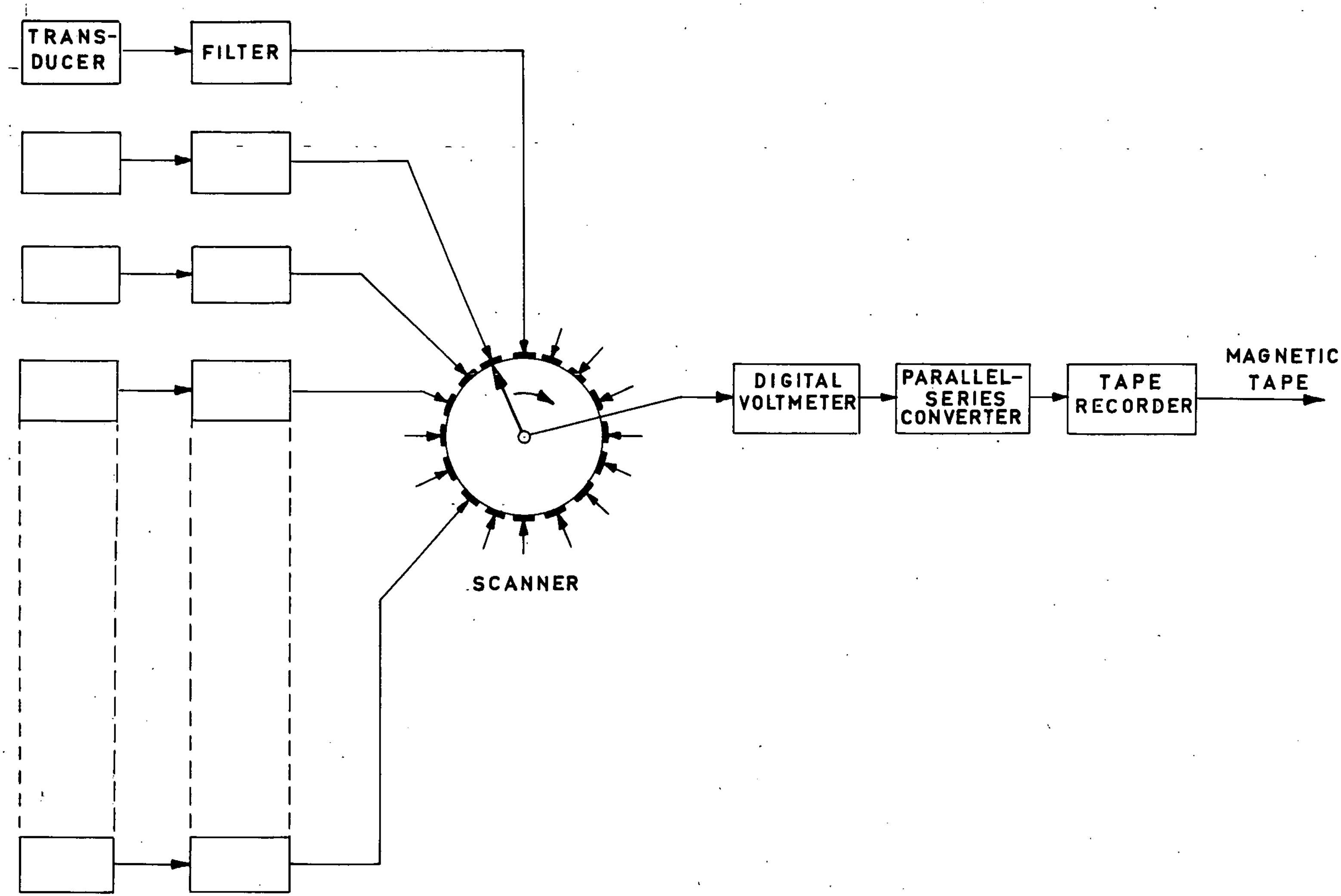


FIG 5 : SIMPLIFIED BLOCK DIAGRAM OF THE INSTRUMENTATION SYSTEM

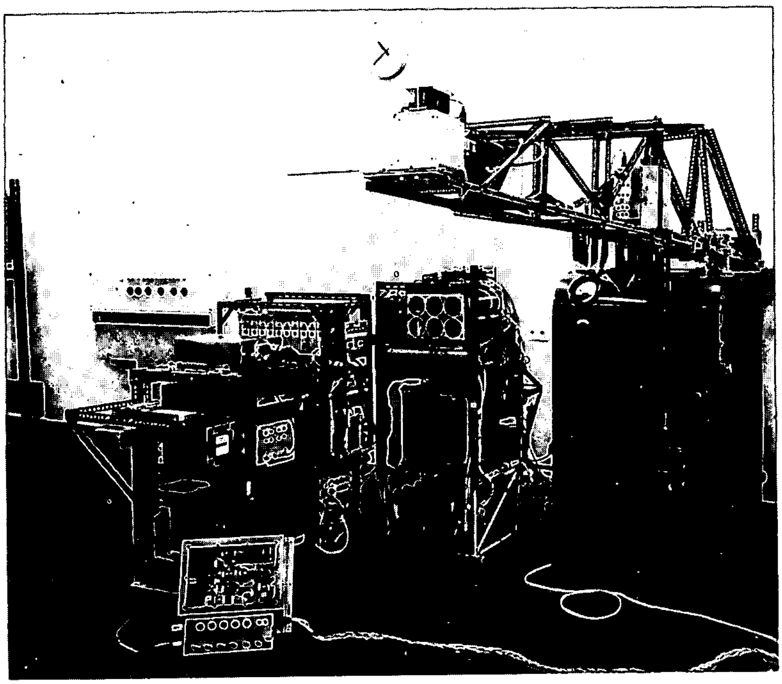
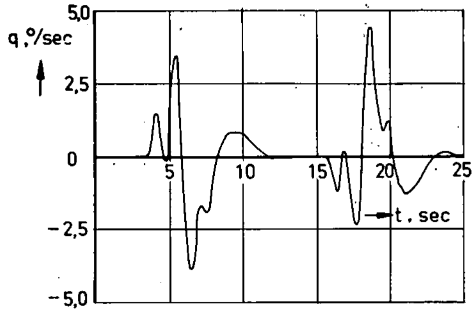
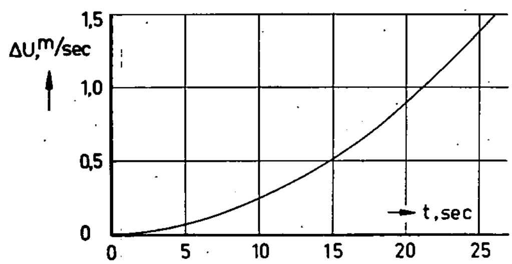


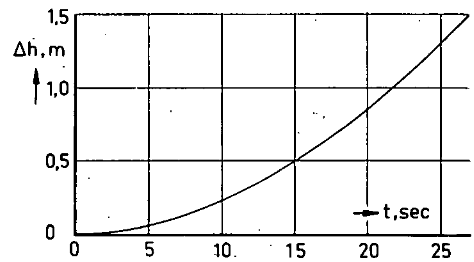
FIG. 6 : SET-UP FOR THE MANOEUVRE SIMULATED IN THE LABORATORY.



a) Rate of pitch q during the simulated manoeuvre

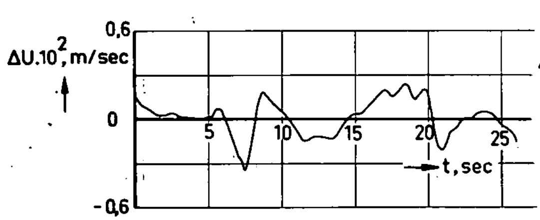


b) Change in horizontal velocity

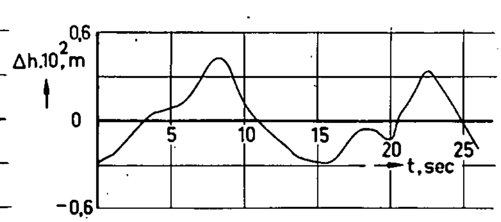


c) Change in height

b. and c. Errors without corrections



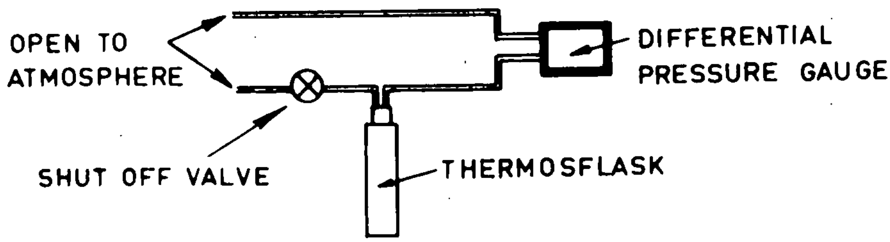
d) Change in horizontal velocity



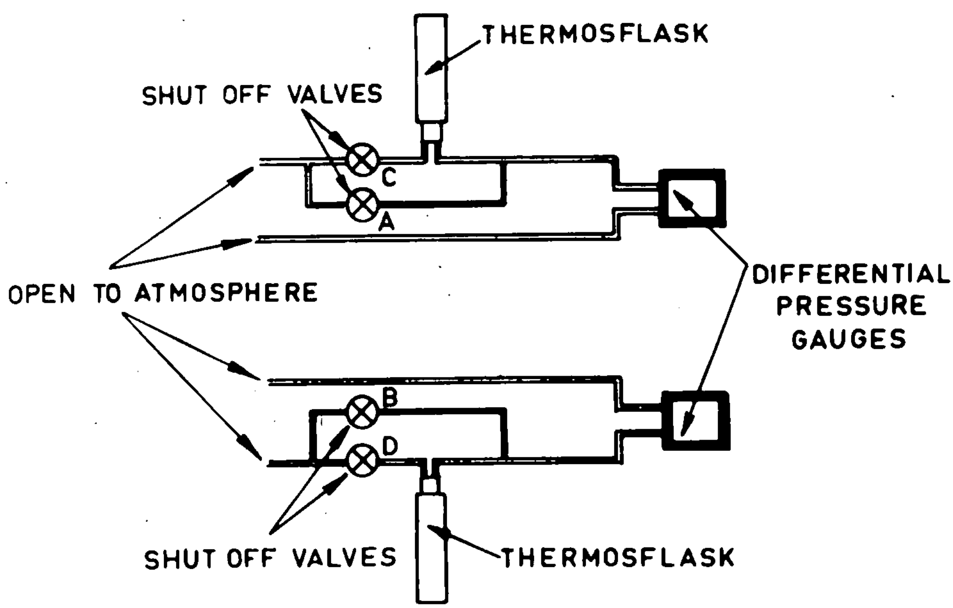
e) Change in height

d and e. Remaining errors after application of corrections based on error-model

FIG. 7: RESULTS OF THE ANALYSIS OF A MANOEUVRE SIMULATED IN THE LABORATORY



a) ELEMENTARY VERSION



b.) MORE COMPLETE VERSION

FIG. 8

SYSTEM TO MEASURE CHANGE IN STATIC PRESSURE

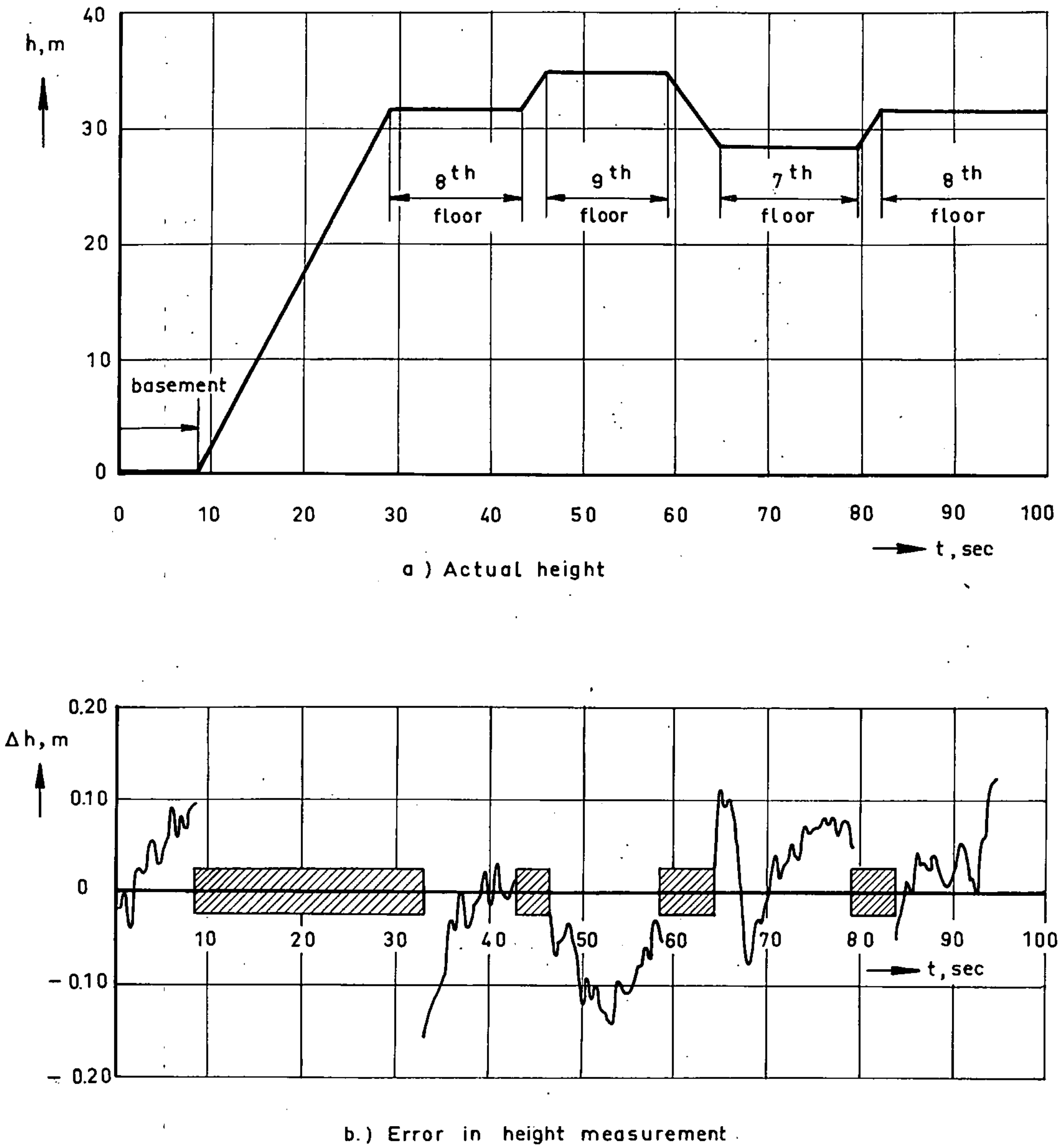


FIG. 9 : DETERMINATION OF CHANGES IN HEIGHT BY MEANS OF PRESSURE MEASUREMENTS

MEASUREMENTS MADE IN THE LIFT OF THE BUILDING OF THE AERONAUTICAL DEPARTMENT AT DELFT

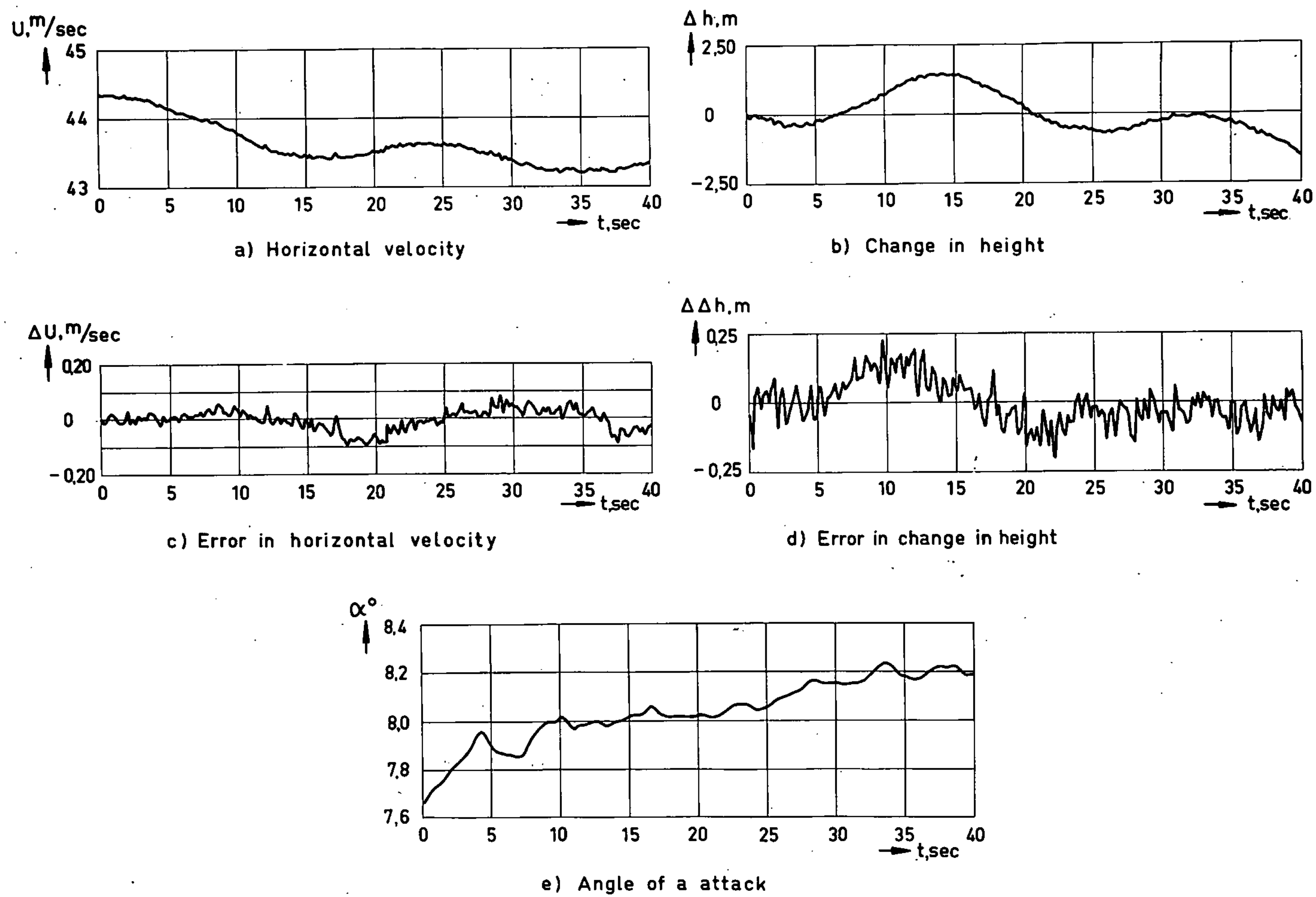
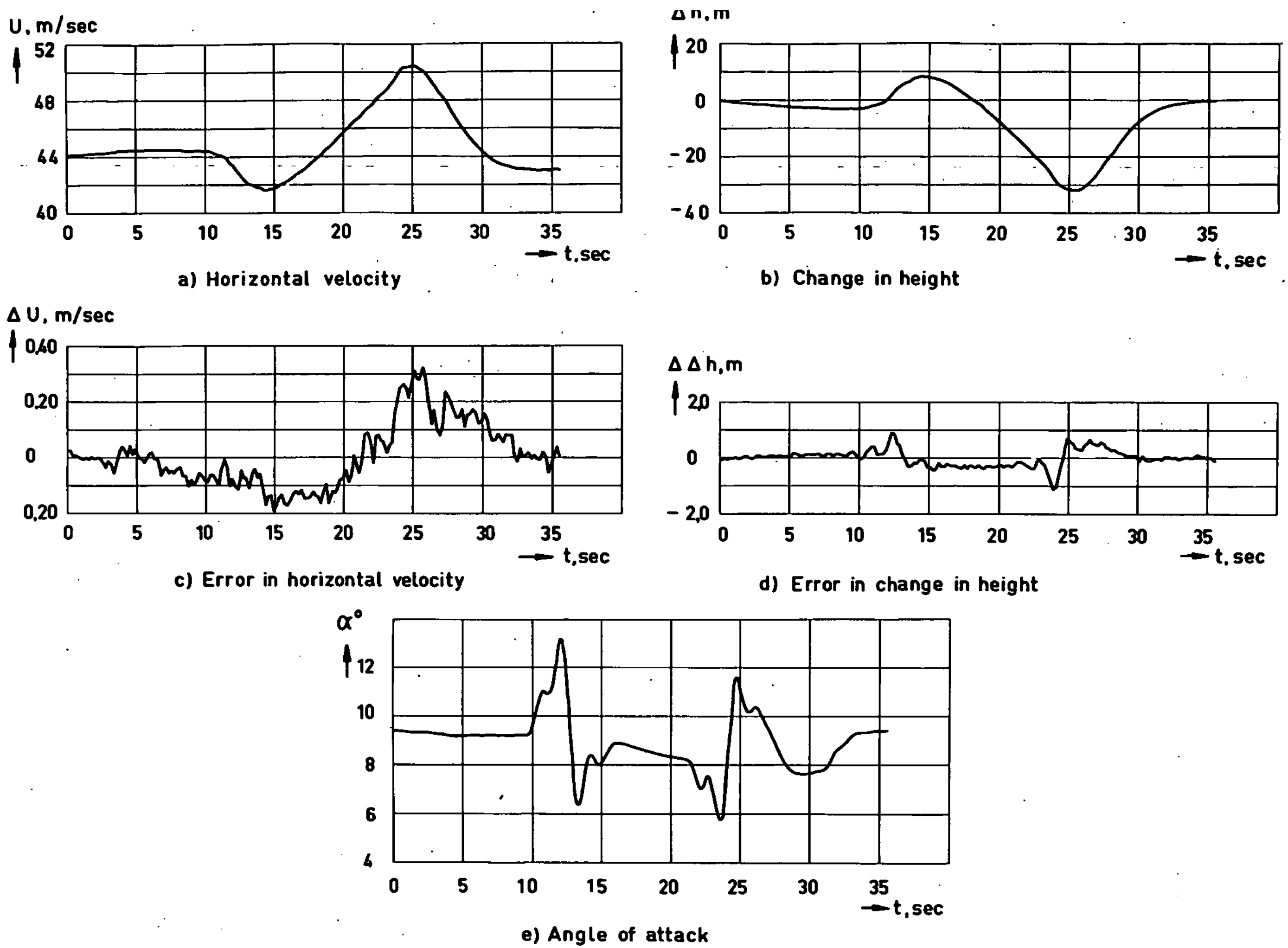


FIG.10 : DETERMINATION OF THE ANGLE OF ATTACK DURING A NEARLY STEADY LEVEL FLIGHT



a) Horizontal velocity

b) Change in height

c) Error in horizontal velocity

d) Error in change in height

e) Angle of attack

FIG. 11: DETERMINATION OF THE ANGLE OF ATTACK DURING A MANOEUVRE

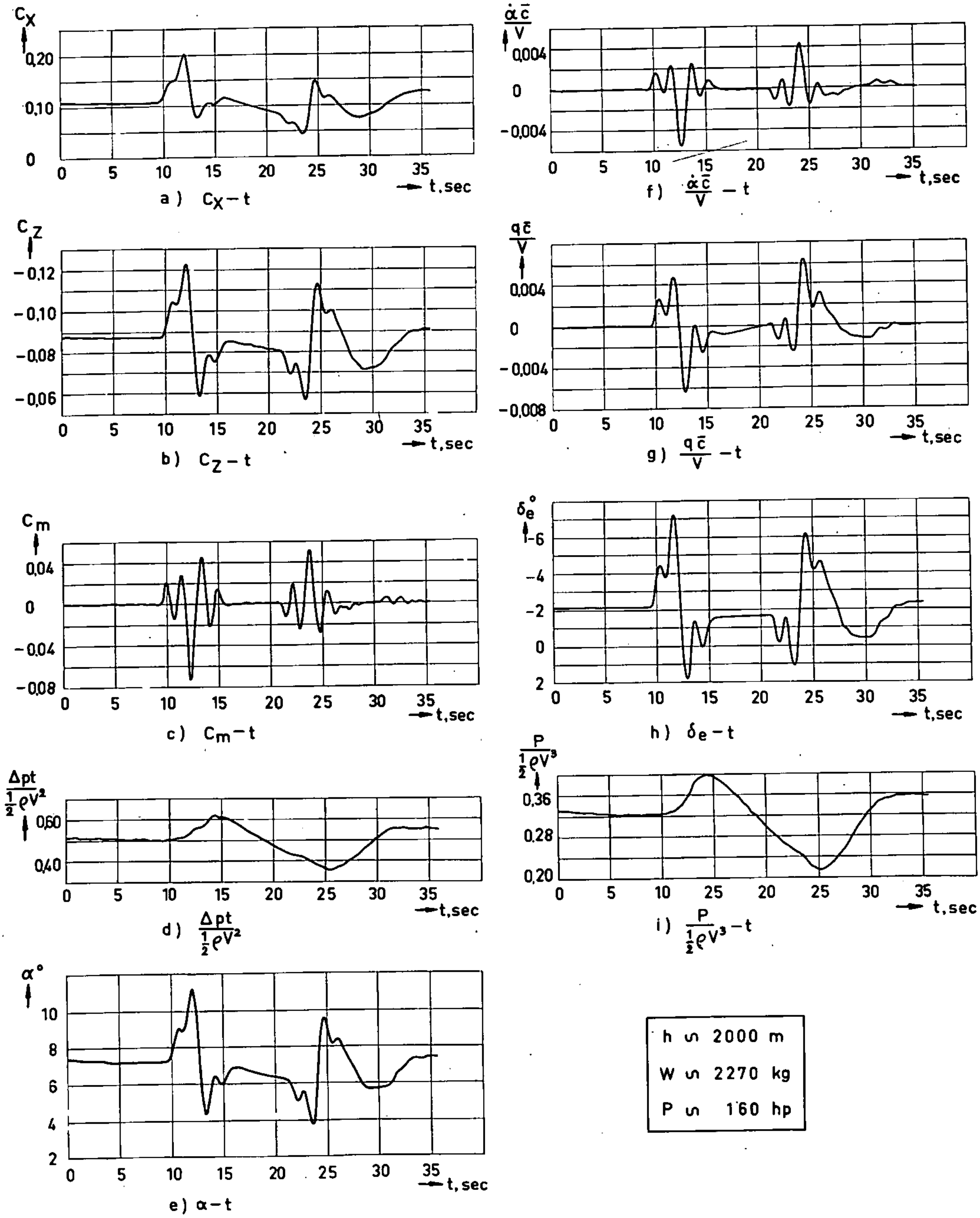


FIG. 12: MEASURED BEHAVIOUR OF SEVERAL VARIABLES DURING A MANOEUVRE

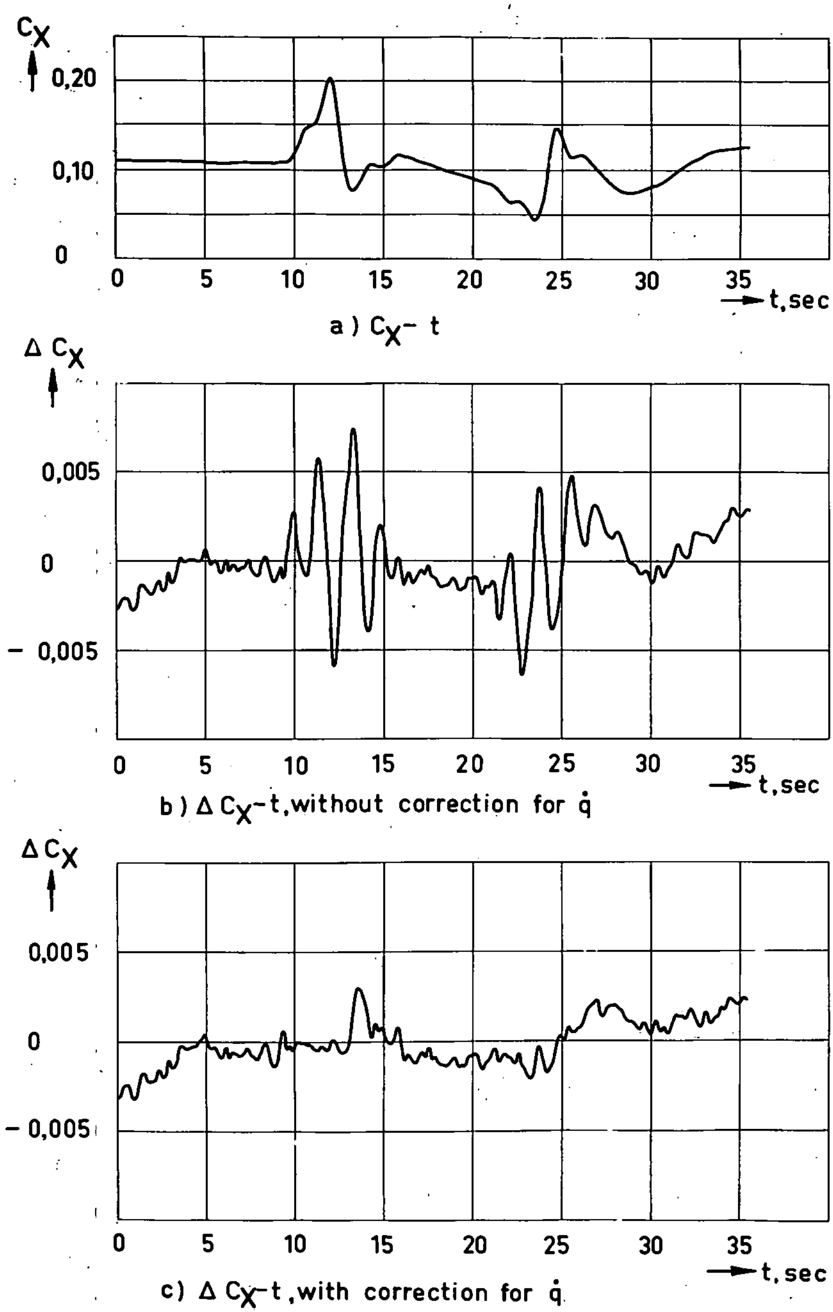
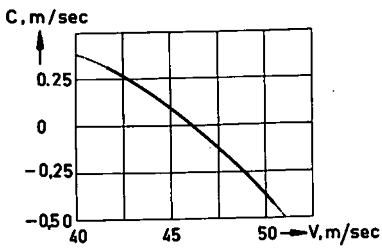
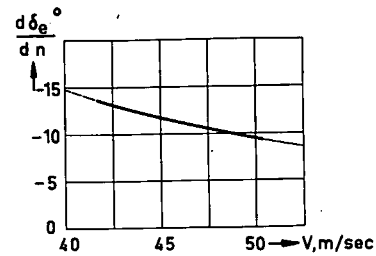


FIG. 13: INFLUENCE OF ANGULAR ACCELERATION $\dot{q}$ SENSED BY THE X − ACCELEROMETER, ON THE DEVIATIONS ΔC_X

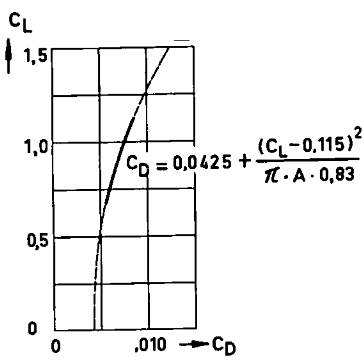
$$\Delta C_X = C_X - \left(C_{X_{\Delta pt}} \cdot \frac{\Delta pt}{\frac{1}{2}\rho V^2} + C_{X_\alpha} \cdot \alpha + C_{X_{\alpha^2}} \cdot \alpha^2 + C_{X_{\dot{\alpha}}} \cdot \frac{\dot{\alpha}\bar{c}}{V} \right)$$



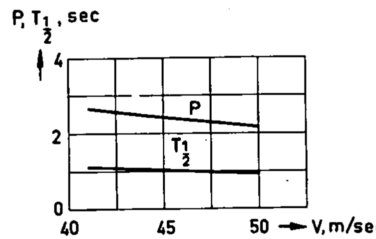
a) RATE OF CLIMB VS. AIRSPEED



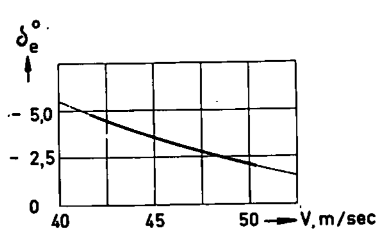
d) STICK-DISPLACEMENT PER "g" VS. AIRSPEED



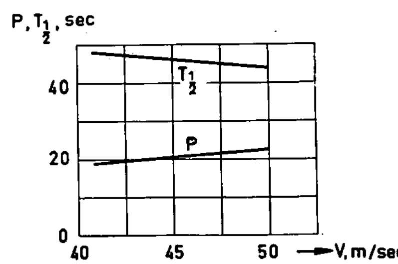
b) POLAR DRAG CURVE



e) PERIOD AND DAMPING OF THE SHORT PERIOD OSCILLATION VS. AIRSPEED



c) TRIM CURVE



f) PERIOD AND DAMPING OF THE PHUGOID OSCILLATION VS. AIRSPEED

h	∽	2000	m
W	∽	2270	kg
P	∽	160	hp

FIG.14 : AIRCRAFT CHARACTERISTICS OBTAINED FROM ONE MANOEUVRE